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J CARTER JAN 84 AFAMRL-TR-84-008 F33615-82-C-0521

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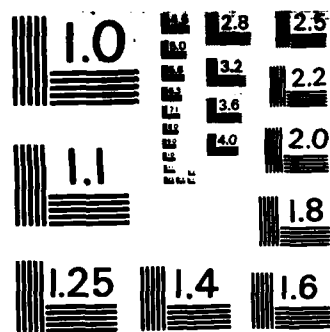
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AFAMRL-TR-84-008

ACTIVE NOISE REDUCTION

JOHN CARTER

BOSE CORPORATION
100 THE MOUNTAIN ROAD
FRAMINGHAM MA 01701

JANUARY 1984



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AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE, OHIO 45433



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Active Noise Reduction (ANR) techniques, singly and in combination with passive hearing protectors, offer the potential for increased sound protection, enhanced voice communications and improved wearability features for personnel exposed to unacceptable noise conditions. An enhanced closed loop active noise reduction system was miniaturized and incorporated into a standard Air Force flight helmet (HGU-26/P). This report describes the theory of design and operation, prototype configuration and operation, and		

electroacoustic performance and specifications for the ANR system. This system is theoretically capable of producing in excess of 30 decibels of active noise reduction. Electroacoustic measurements on a flat plate coupler demonstrated approximately 20 decibels of active noise reduction with the prototype unit. A performance evaluation of the integrated ANR unit will be conducted under laboratory and field conditions by government personnel to determine the feasibility of the system for use in military applications.

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TECHNICAL REVIEW AND APPROVAL

AFAMRL-TR-84-008

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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PREFACE

This report describes work that involved the fabrication of an Active Noise Reduction (ANR) system and its integration into an Air Force flight helmet. The work was accomplished by the BOSE Corporation under Air Force Contract F33615-82-C-0521. This effort was supported by the Life Support Systems Program Office, Operational Systems Support Division, Aeronautical Systems Division and technically administered by the Biological Acoustics Branch, Biodynamics and Bioengineering Division, Aerospace Medical Research Laboratory. It was accomplished under Project 7231, "Biomechanics of Aerospace Operations" and Task 723103, "Communication and Performance Capability in Operational Noise." Air Force project engineers were Mr. Richard McKinley and Lt William Decker. BOSE personnel responsible for the work were John Carter, Roman Sapiejewski, Dan Gauger and Norman Stickney.

INTRODUCTION

In many noise environments it is not practical, economical or feasible to reduce noise levels at the ear of a listener to within acceptable limits using engineering controls. In some of these situations an acceptable noise level at the ear may be achieved with the use of personal hearing protection in the form of ear plugs, earmuffs, helmets or combinations of these devices. In other situations, the performance of the hearing protector is not fully acceptable allowing noise levels at the ear that may interfere with activities, degrade performance or even pose a threat to hearing, if of appropriate magnitude, frequency and duration. The concept of active noise reduction (ANR) was successfully demonstrated several decades ago as a potential means of enhancing the performance of hearing protection to provide satisfactory communication and protection in situations where they are not achievable with passive devices. At that time, various instrumentation and system constraints prevented the concept from being reduced to practice. Recently, the BOSE Corporation demonstrated a laboratory prototype Active Noise Reduction system that appears to have resolved most of the major constraint problems of the earlier systems and to have created the potential for a practical ANR system.

PURPOSE

The purpose of this project is to evaluate the effectiveness of hearing protection and voice communication performance with the BOSE Corporation active noise reduction technique integrated into an Air Force flight helmet. The purpose of this report is to describe the active noise reduction system, its operation and its performance.

BACKGROUND

Three fundamental types of active noise reduction have been demonstrated with varying degrees of success; open loop, closed loop and digital adaptive systems. These systems vary in complexity, advantages-disadvantages, and effectiveness. Although there are variations in theory and operation of these systems, they all operate on the principle of noise cancellation at the ear.

Open loop active noise reduction systems operate by measuring the noise outside the ear enclosure, adjusting the spectrum and level to approximate those of the noise inside the enclosure, inverting the phase of the signal 180 degrees and presenting the adjusted signal to cancel the noise inside the ear enclosure. Figure 1 shows a block diagram of this approach. Cancellation is only partially successful because the adjustment of spectrum and level is strongly dependent upon the seal and the fit of the enclosure which varies from user to user. Its effectiveness is limited to frequencies below about 800 Hz. The open loop system may produce more noise inside the enclosure than the passive system alone if it is operating improperly. The open loop system requires an effective acoustic seal of the ear enclosure for satisfactory operation.

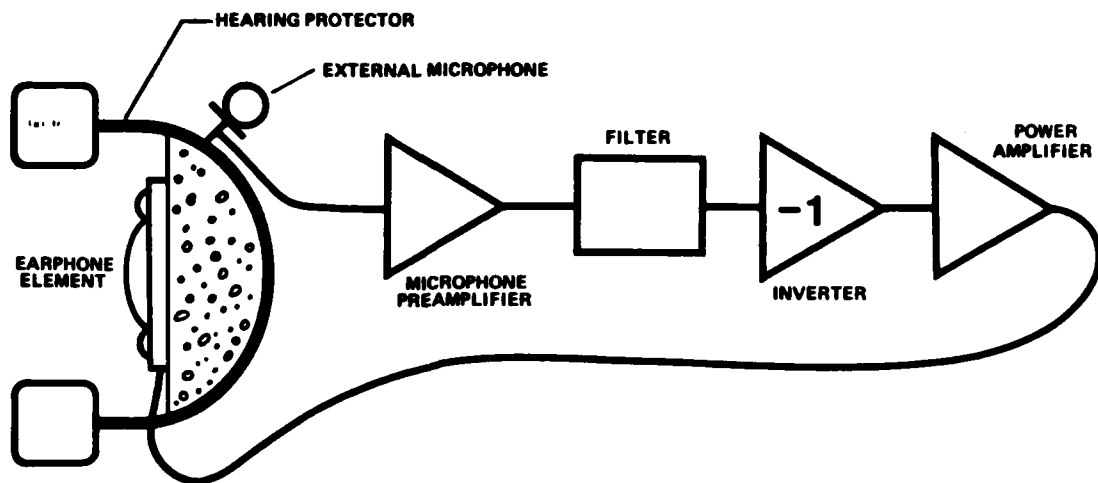


Figure 1. Block Diagram of Open Loop Active Noise Reduction System.

The adaptive digital noise reduction technique operates in an open loop mode where the adjustments of the outside signal to form the cancellation signal are done with digital techniques that continually adapt to changes in the outside noise signal. This system is shown in Figure 2. The speed with which the outside noise is digitized, processed and reconstructed is less than actual real time and a consequence is that the transient sound is not really eliminated. Adaptive digital techniques may be more costly than the more conventional analog systems. Their effectiveness is limited to frequencies of about 800 Hz and below and the amount of noise reduction is expected to be about 6 to 12 dB.

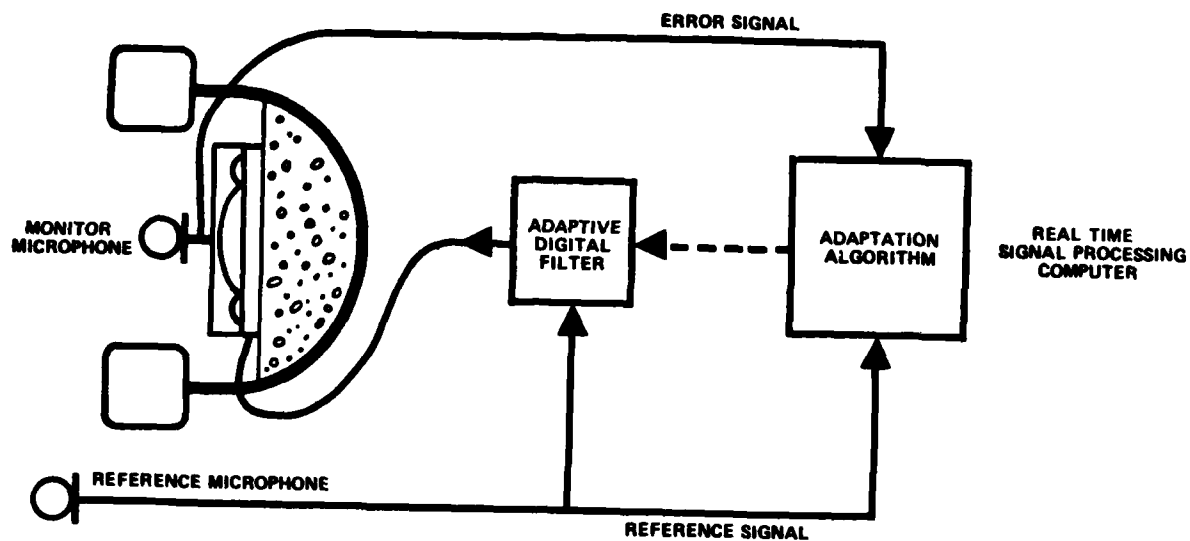


Figure 2. Block Diagram of Adaptive Digital Noise Reduction System.

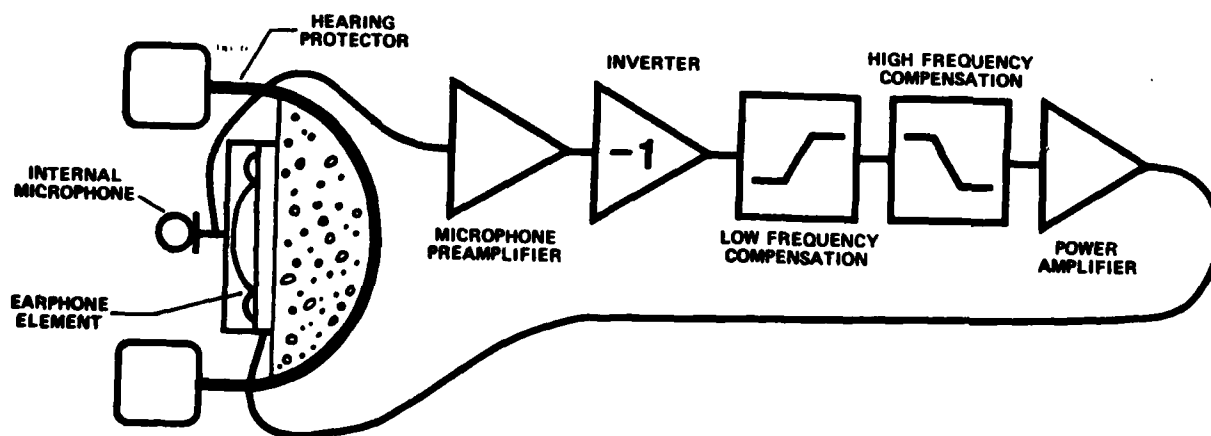


Figure 3. Block Diagram of Closed Loop Active Noise Reduction System.

Closed loop systems operate on essentially the same principles as the open loop systems except that the initial measurement of the noise takes place inside the ear enclosure. The primary advantage of the closed loop over open loop systems is that the process of adjusting the measured noise to become a cancellation signal is greatly simplified. The noise measured inside the enclosure is continuously corrected to match the input signal, shifted 180 degrees in phase and reintroduced to achieve the cancellation. Figure 3 shows a block diagram of the closed loop approach. The closed loop system may be expected to provide better performance than open loop because of the somewhat more efficient cancellation signal. Time delay in the prototype system limits the noise reduction effectiveness to frequencies below about 800 Hz. An acoustic seal of the ear enclosure is not essential to the successful operation of the closed loop noise reduction system.

The BOSE Corporation active noise reduction system is an enhanced closed loop system. The proprietary methodology of "frequency domain optimal compensation" developed by BOSE has been incorporated into their prototype Model 2081. Model 2081 is theoretically capable of producing active noise reductions that will exceed 30 decibels. The frequency response of the system is reasonably flat and the output signal has low distortion. The theory of design of the BOSE Corporation Model 2081 system is described in Appendix II.

A comparative evaluation of these active noise reduction techniques reveals that the advantages of the BOSE Model 2081 active noise reduction prototype make it the logical choice for investigating the feasibility of ANR in military applications.

APPROACH

The BOSE Model 2081 active noise reduction system has been miniaturized and incorporated into a standard Air Force flight helmet (HGU-26/P). The modification includes fabrication of appropriate cables and connectors to allow the ANR helmet to be mated either with laboratory equipment or with AF aircraft communication systems.

The Integrated ANR (IANR) helmet will be evaluated in laboratory tests by BOSE Corporation for appropriate electronic performance and for active, passive and active-passive noise reduction on a flat plate coupler. The IANR helmet will be transported to AFAMRL/BBA for additional laboratory and field tests. Data from these tests will be analyzed to determine the feasibility of the BOSE ANR for military applications.

BOSE PROTOTYPE CONFIGURATION

The IANR assembly includes the helmet with headset earcups, two small metal boxes (approximately 4" x 8" x 2" overall) containing the electronics and appropriate cables. The active noise reduction transducers (exploded view in Figure 4) are contained in the helmet mounted earcups and the electronics in the smaller metal box (approximately 4" x 3" x 1.5"). The larger box contains a separate power supply for the prototype that utilizes 110 Vac, 60-400 cycle. One of the three cables is for external power to the power supply, one is the connection to the aircraft intercommunications system and one is connected to the oxygen mask or boom microphone. The overall configuration is highly suited to laboratory and field tests because of its relatively small size and light weight. A photograph of the electronics and earcups is shown in Figure 5.

PROTOTYPE OPERATION

Operation of the IANR system requires that all cable connections be completed and the helmet properly fit so that the earcups are positioned over the ears of the wearer. The connectors and the controls of the unit are clearly marked as displayed in Figure 6. Only two controls are required for operation; both the power switch and the noise cancellation switch must be in the "on" position. The noise cancellation switch in the "off" position bypasses the active noise reduction system. This feature is provided to allow the wearer to readily compare system effectiveness by switching back and forth from ANR (switch "on") to no ANR (switch "off"). Appendix I contains a Users Guide that explains the functions of the jacks, connectors and switches.

THEORY OF OPERATION

The theoretical operation of the BOSE 2081-AF Active Noise Reduction System may be viewed relative to the expanded block diagram of Figure 7. In normal operation, the active noise reduction system is activated and the feedback system senses any acoustic noise and acts to reduce it. Also, it passes any input communication signal to the driver so that communication can take place while active noise reduction occurs. In order to understand the complexity of the active noise reduction system, a schematic diagram for one channel is shown in Figure 8. The system requires standard electronic components and could yield to miniaturization.

The frequency response in the normal mode of operation is shown in Figure 9, the closed loop gain. The closed loop gain path includes a pre-equalizer which flattens the response from 1000 to 6000 Hz. This region was not as flat as specified in the original proposal because of the need for a higher dynamic range which required a larger driver. The larger transducer causes response irregularities to occur at higher frequencies.

The active noise reduction function is eliminated when the noise cancellation switch is in the "off" position, however, the communication signal is still applied to the driver. A bypass equalizer is required because the response of the driver is not flat without the servo system as it is when the noise reduction is activated. The bypass equalizer approximates the response of the closed loop system. It is difficult to equalize both paths to be exactly the same because the response of the driver is fairly irregular above 3000 Hz. However, they are very close if the responses are viewed in terms of octave bands.

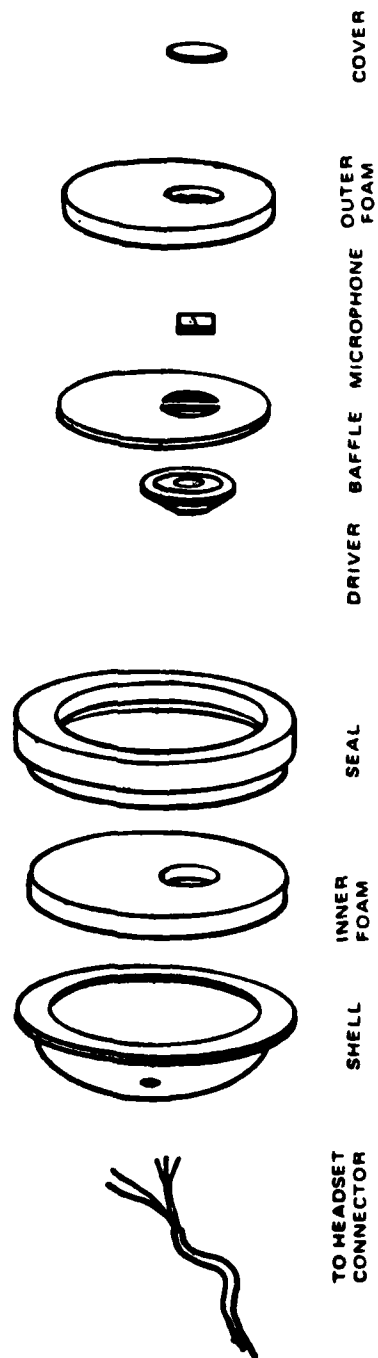


Figure 4. Acoustical Package of the BOSE 2081-AF Active Noise Reduction System.

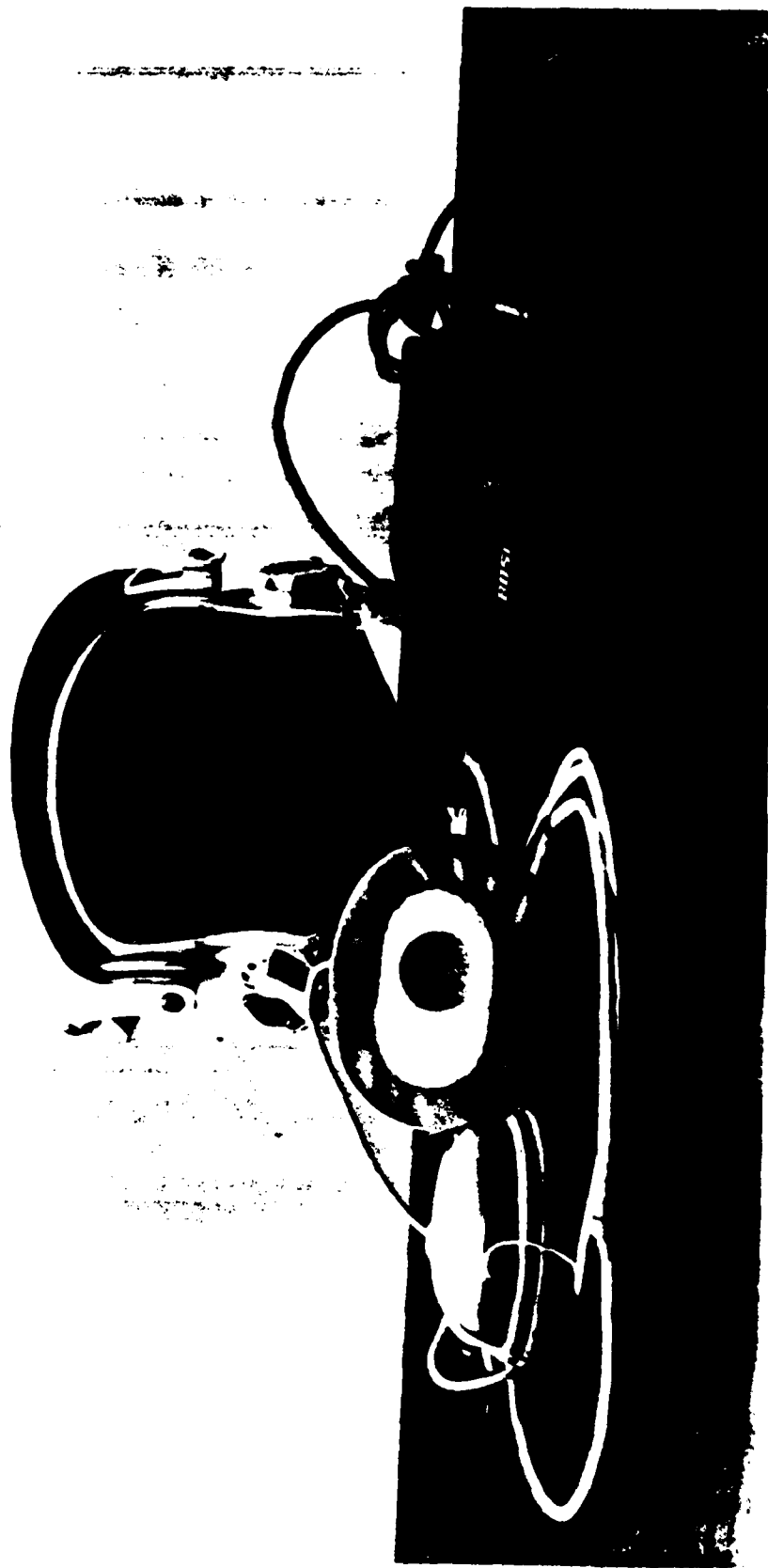


Figure 5. Photograph of the ANR Electronics Package and Earcups .



Figure 5. Photograph of the ANR Electronics Package
and Earcups

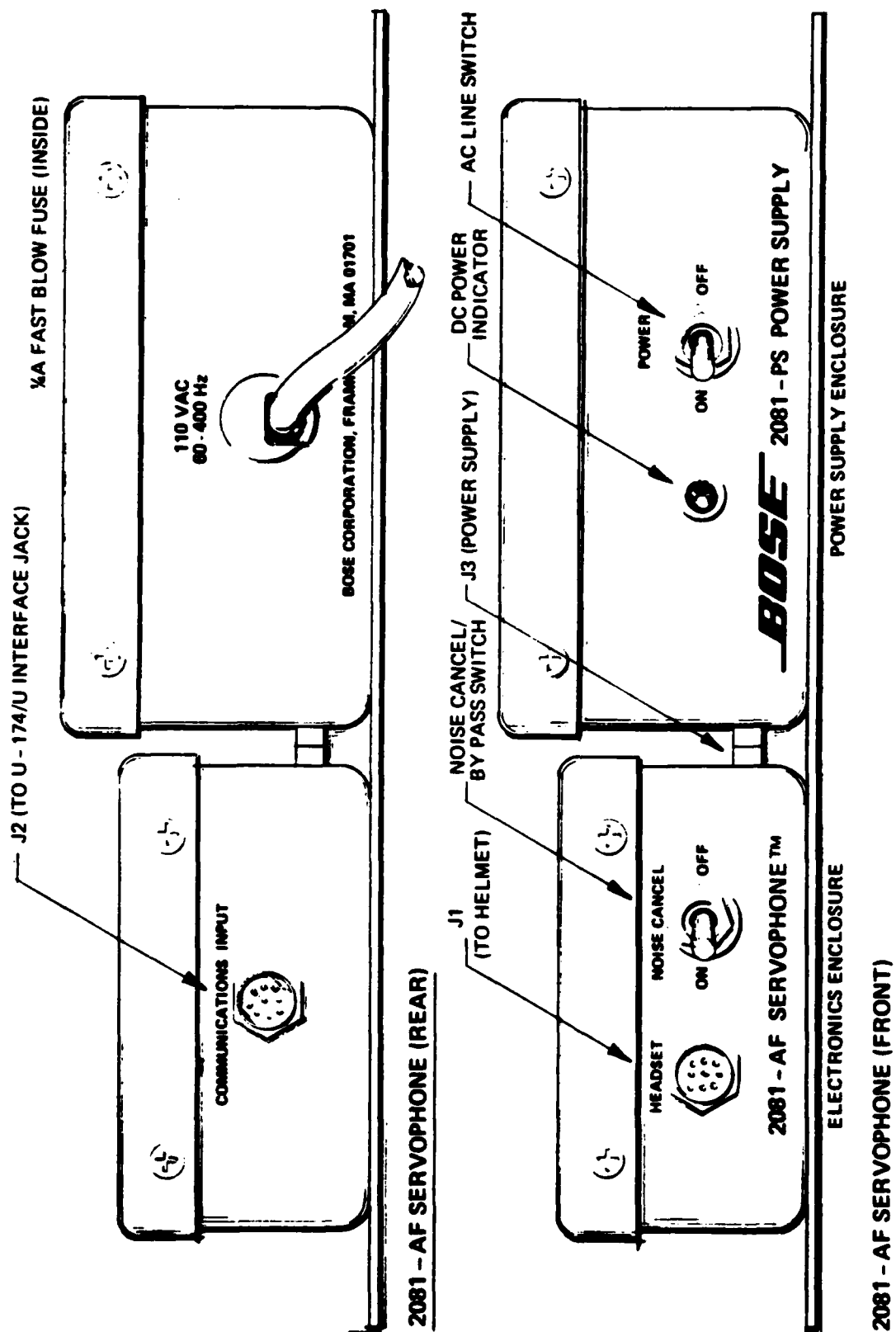


Figure 6. Mechanical Package of the BOSE 2081-AF Active Noise Reduction System.

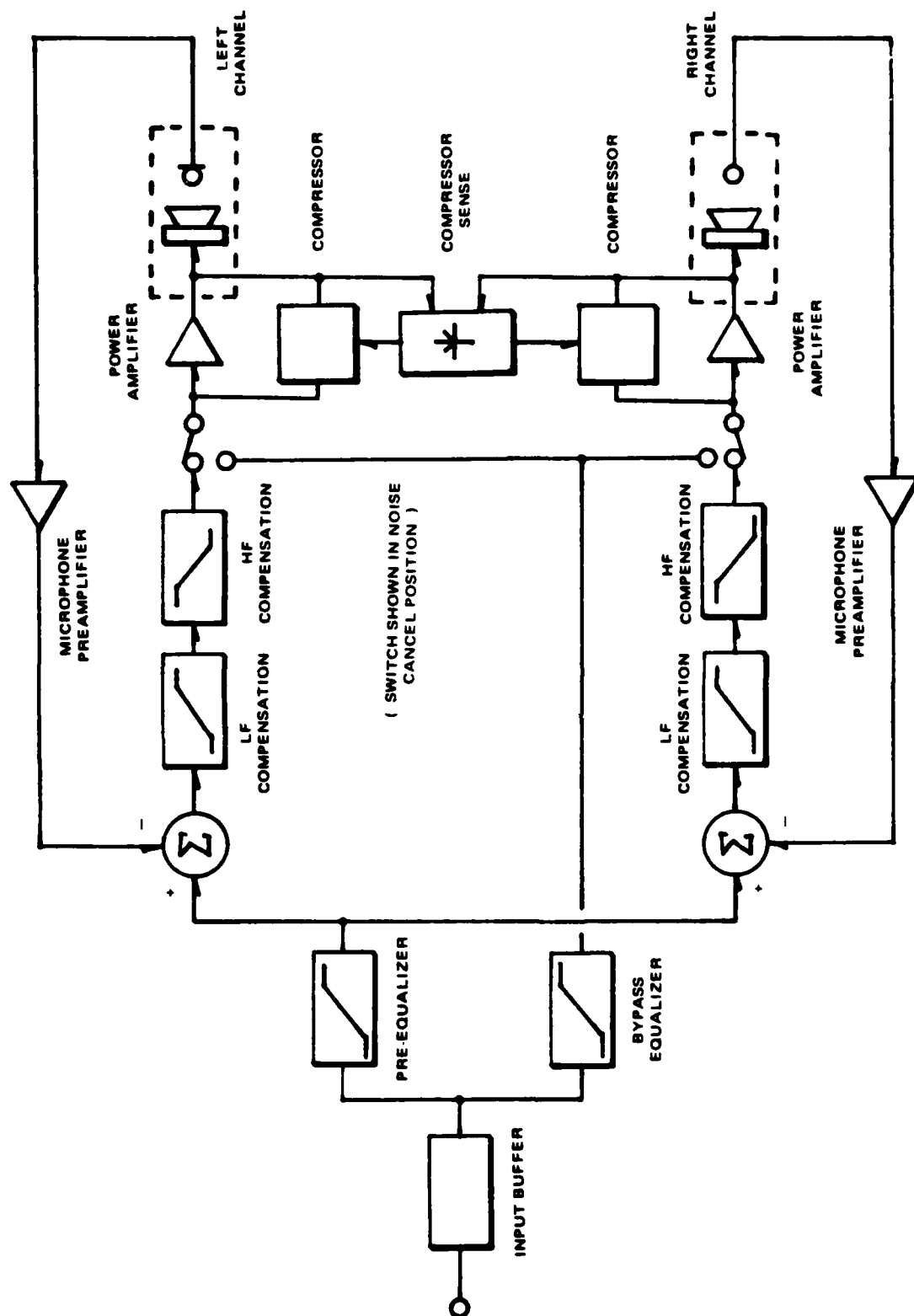


Figure 7. Expanded Block Diagram of a BOSE 2081-AF Active Noise Reduction System. Note that bypass equalization is included to promote accurate system evaluation when servo loop is deactivated by the noise cancel switch.

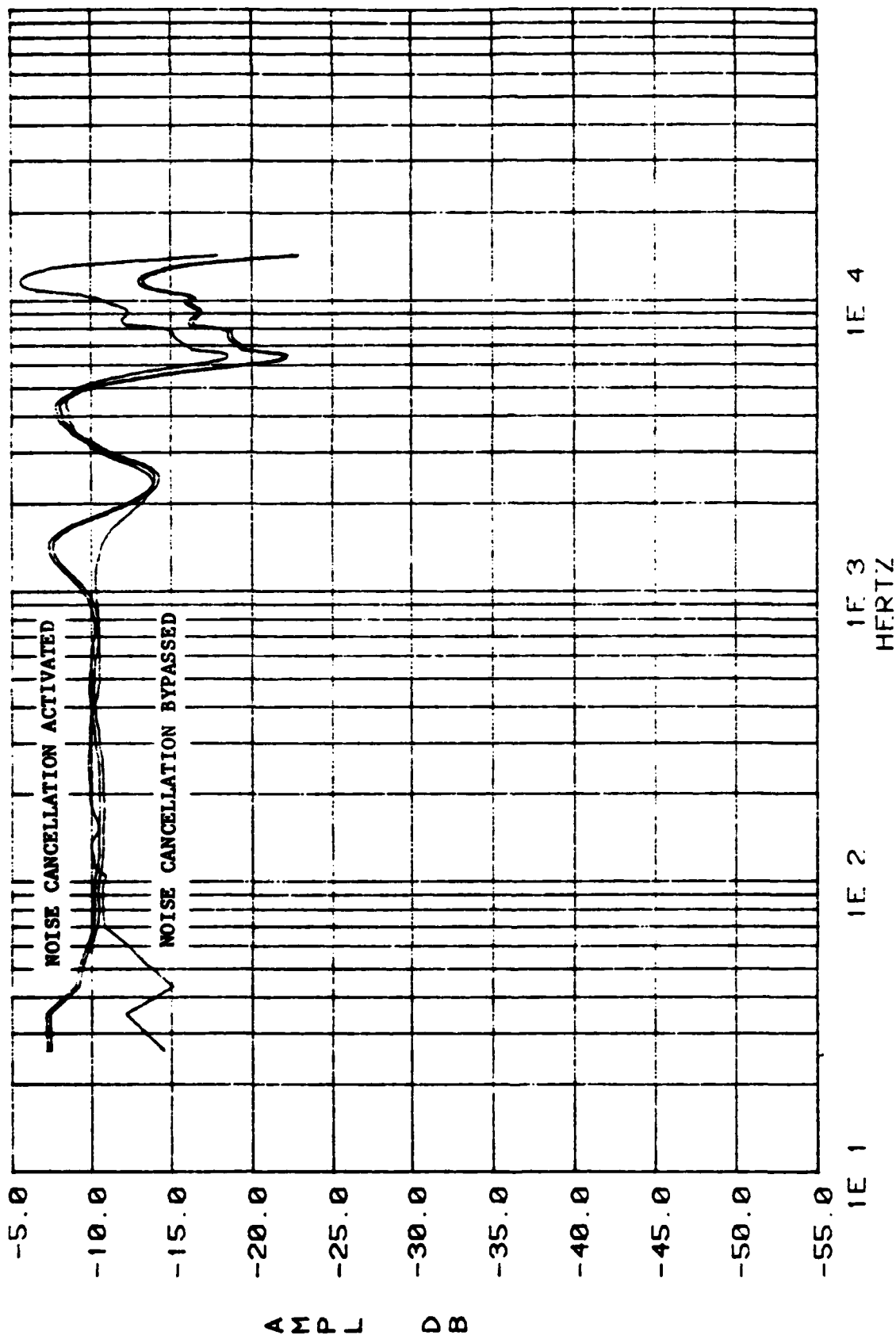


Figure 9. Frequency Response of Communication Channel Through the System With and Without Active Noise Cancellation.

The prototype also includes compressor circuits to counteract large acoustic transients that cause the system to clip peaks, creating spurious sounds in the earcup. The loop gain is reduced when signals are detected that would cause the power amplifier to clip. This has two effects; first, it prevents large acoustic signals from reaching the ear. Second, it reduces the amount of active noise reduction. In normal operation (i.e., sound fields up to 125 dB(C)) the compressor is not operational. However, it will operate automatically when the earcup is mechanically displaced, or when the system is subject to a large acoustic transient. The compressor has very sharp "turn-on" characteristics as a function of level.

ELECTROACOUSTIC PERFORMANCE AND ENGINEERING SPECIFICATIONS

All performance tests reported herein were conducted at the BOSE Corporation on a flat plate acoustic coupler, unless noted. The acoustic coupler contained a B & K 4134, 1/2 inch microphone positioned with the grid flush with the plate surface. A 0.5 kg mass was placed on the earcup positioned on the flat plate coupler to provide the same force for all earcups measured during the performance tests. The following section is numbered in accordance with other BOSE specifications.

1.0 PERFORMANCE SPECIFICATIONS

- 1.1 Open Loop Gain. This is the quantity GH as discussed in Appendix II that characterizes the overall performance level of the system. See Figures 10 and 11.
- 1.2 Acoustical Isolation. Active Component - This flat plate measurement does not include the passive attenuation provided by the earcup enclosure. See Figures 10 and 11.
- 1.3 Acoustical Isolation. Passive and Total Components - See Figures 12 and 13.
- 1.4 Maximum Sound Pressure Level for Cancellation: 124 dB Pink noise of 60 Hz to 6000 Hz; 4:1 crest factor, as measured in reverberant room (C weighted).
- 1.5 Electrical Power Output (per channel): 1W 15 Hz to 6000 Hz, 100 ohm load.
- 1.6 A sine wave is applied to the communication signal input. Acoustical, 105 dB SPL output.

<u>Frequency</u>	<u>%THD</u>
60 Hz	5
120 Hz	2
240 Hz	1
500 Hz	0.5
1000 Hz	0.2
2000 Hz	0.5
4000 Hz	1

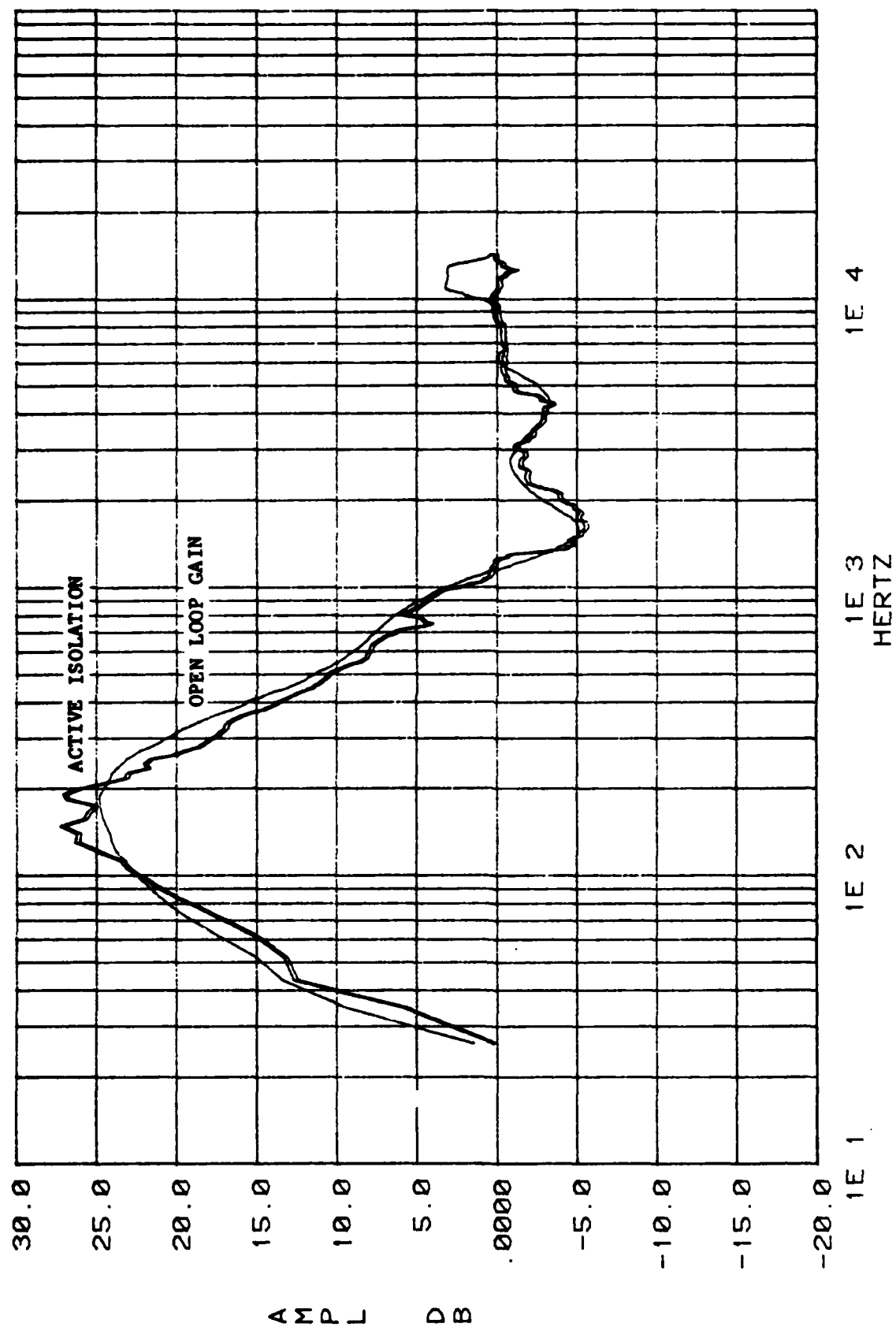


Figure 10. Active Acoustic Isolation and Open Loop Gain for the BOSE 2081-AF Active Noise Reduction System - Left Channel.

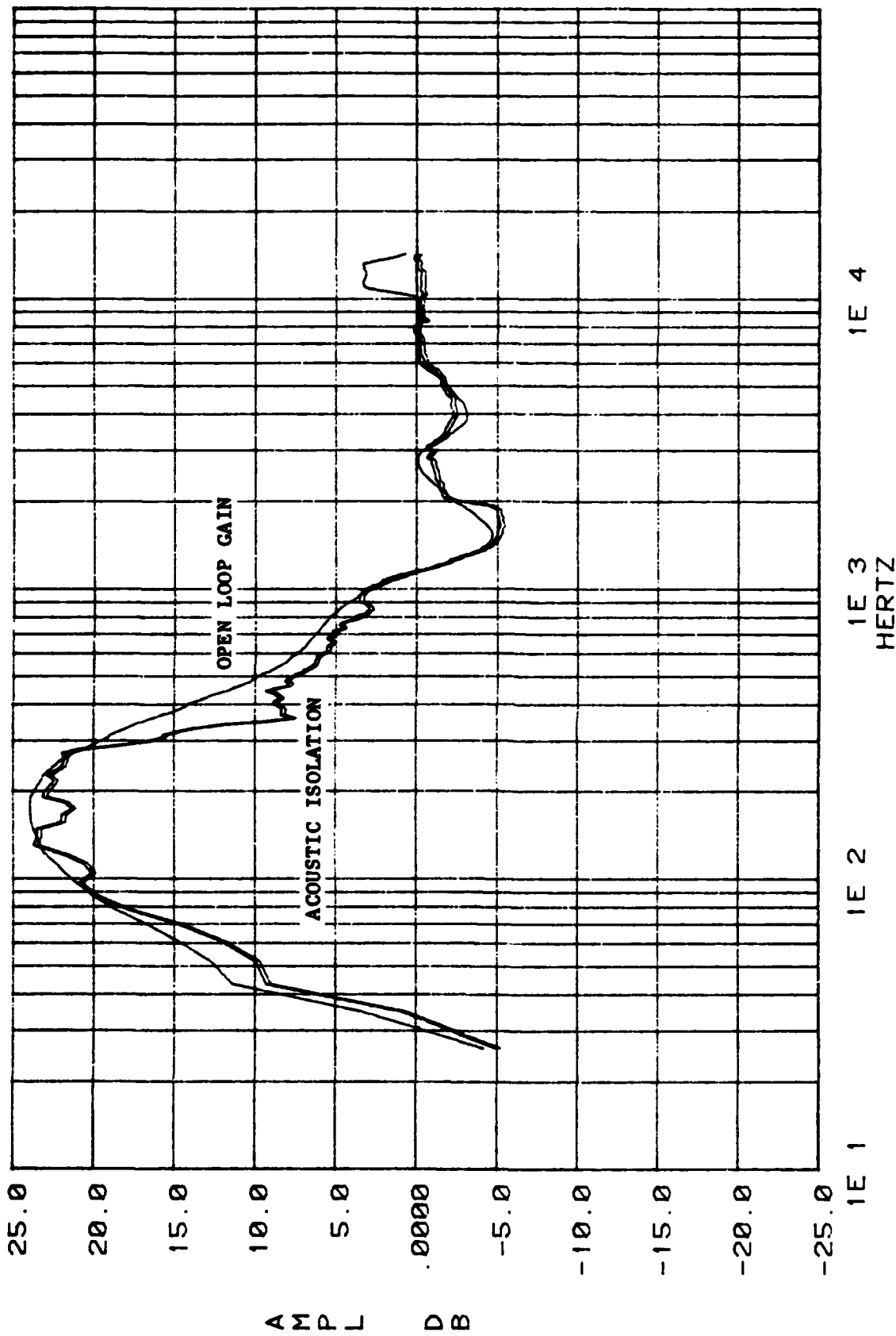


Figure 11. Active Acoustic Isolation and Open Loop Gain for the BOSE 2081-AF Active Noise Reduction System - Right Channel.

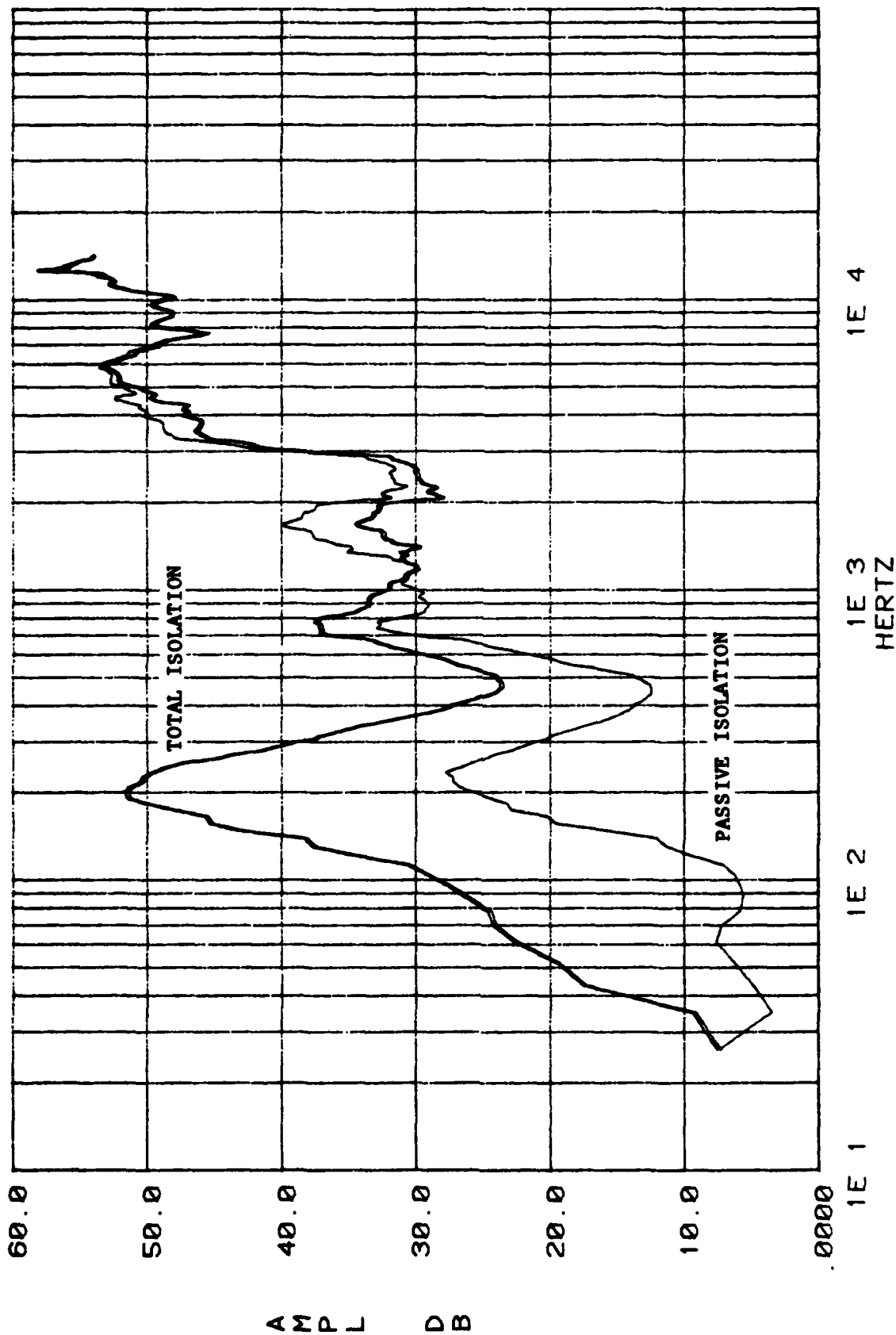


Figure 12. A Comparison of Passive and Total Acoustical Isolation - Left Channel.

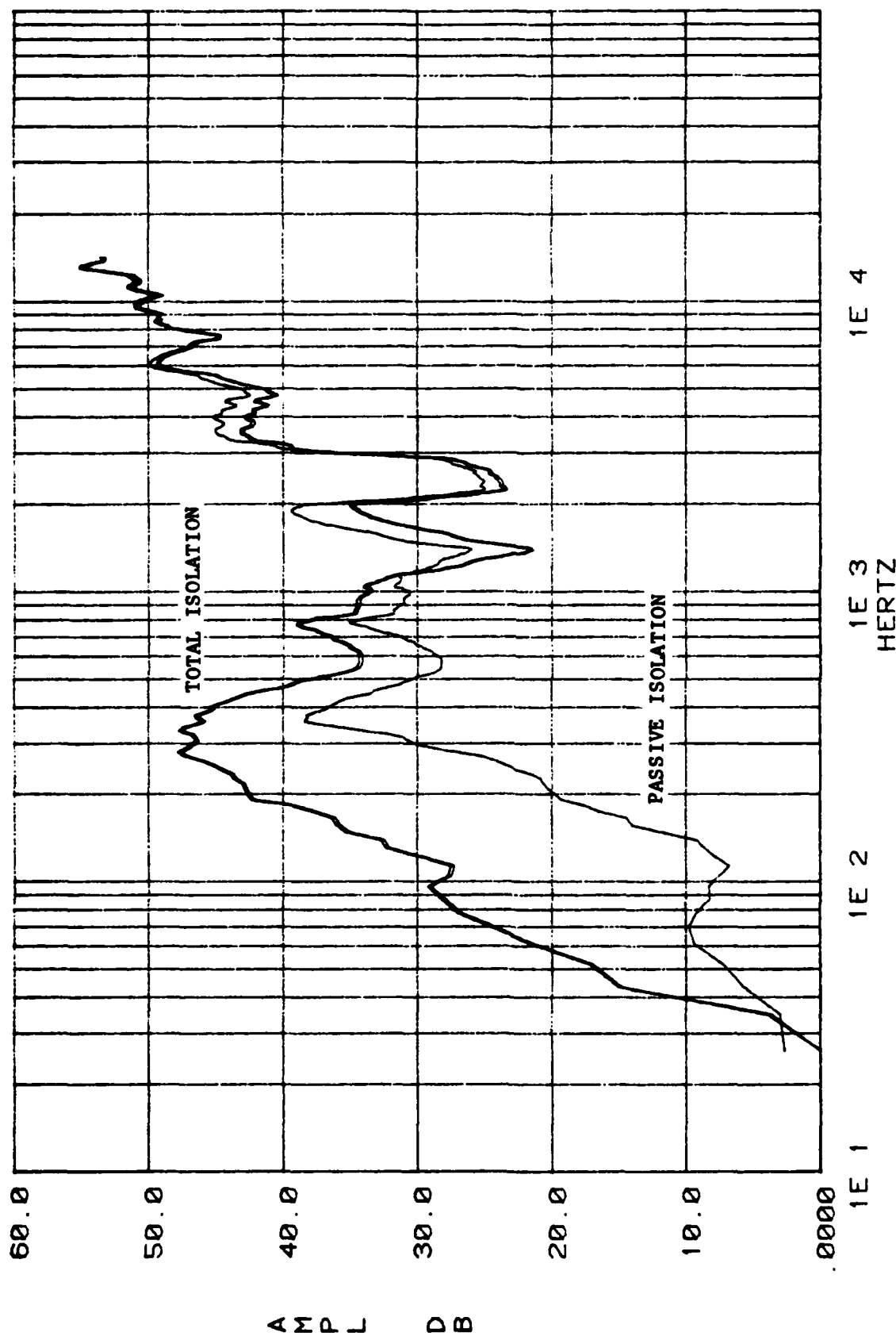


Figure 13. A Comparison of Passive and Total Acoustical Isolation - Right Channel.

1.7 Acoustical Frequency Response

60 Hz - 6000 Hz +/- 5.0 dB maximum

60 Hz - 3000 Hz +/- 3.0 dB

See Figures 14 and 15, Closed Loop Response. The closed loop frequency response is the response of the system to communication signals at the input.

Figures 14 and 15 also show the response when the noise cancel switch is in the off position. This is an equalized frequency response designed to approximate the noise cancel in response. This switch allows one to evaluate active noise reduction without changing the frequency response.

1.8 Channel Balance

2.0 dB at 1000 Hz

1.9 Input Impedance

10,000 ohms

1.10 Signal-to-Noise Ratio

74 dB(A), reference to 105 dB SPL

1.11 Compressor-Limiter

A compressor prevents the power amplifier from clipping when the system is subject to mechanical or acoustic overloads. It acts only when the level is greater than 125 dB SPL.

1.12 AC Power Requirements

110 Vac, 60 - 400 Hz

1.13 Power Consumption

2.5 watts in 105 dB SPL noise field (power to electronics).

2.0 MECHANICAL DESIGN

2.1 Controller

See Appendix I, User's Guide.

2.2 Headset

Driver and microphone required for servo system to be built into modified HGU-26/P, flight helmet.

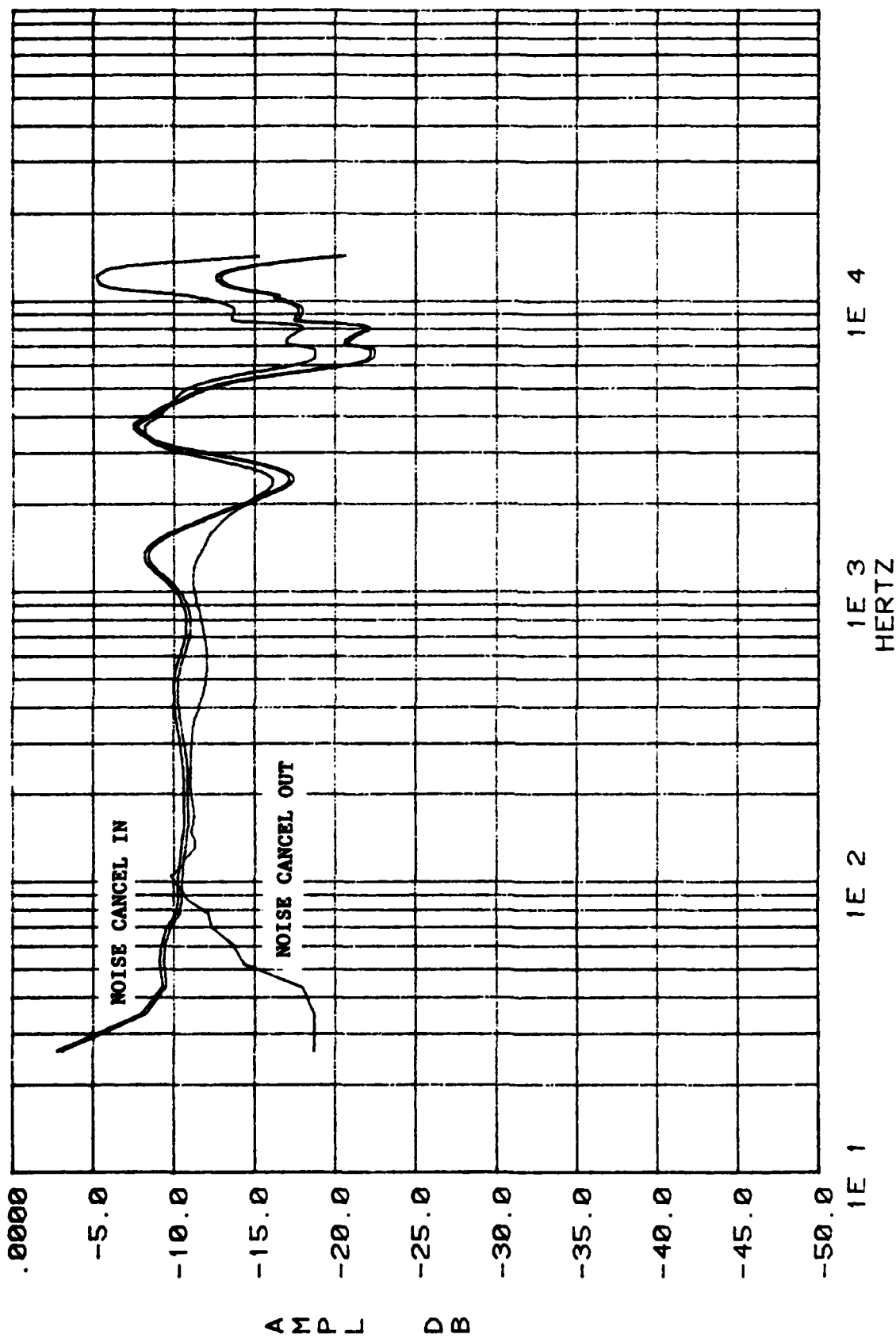


Figure 15. Frequency Response of the 2081-AF System From Communication Input to Earphone Output, Shown With Noise Cancel Switch in Both Positions - Right Channel.

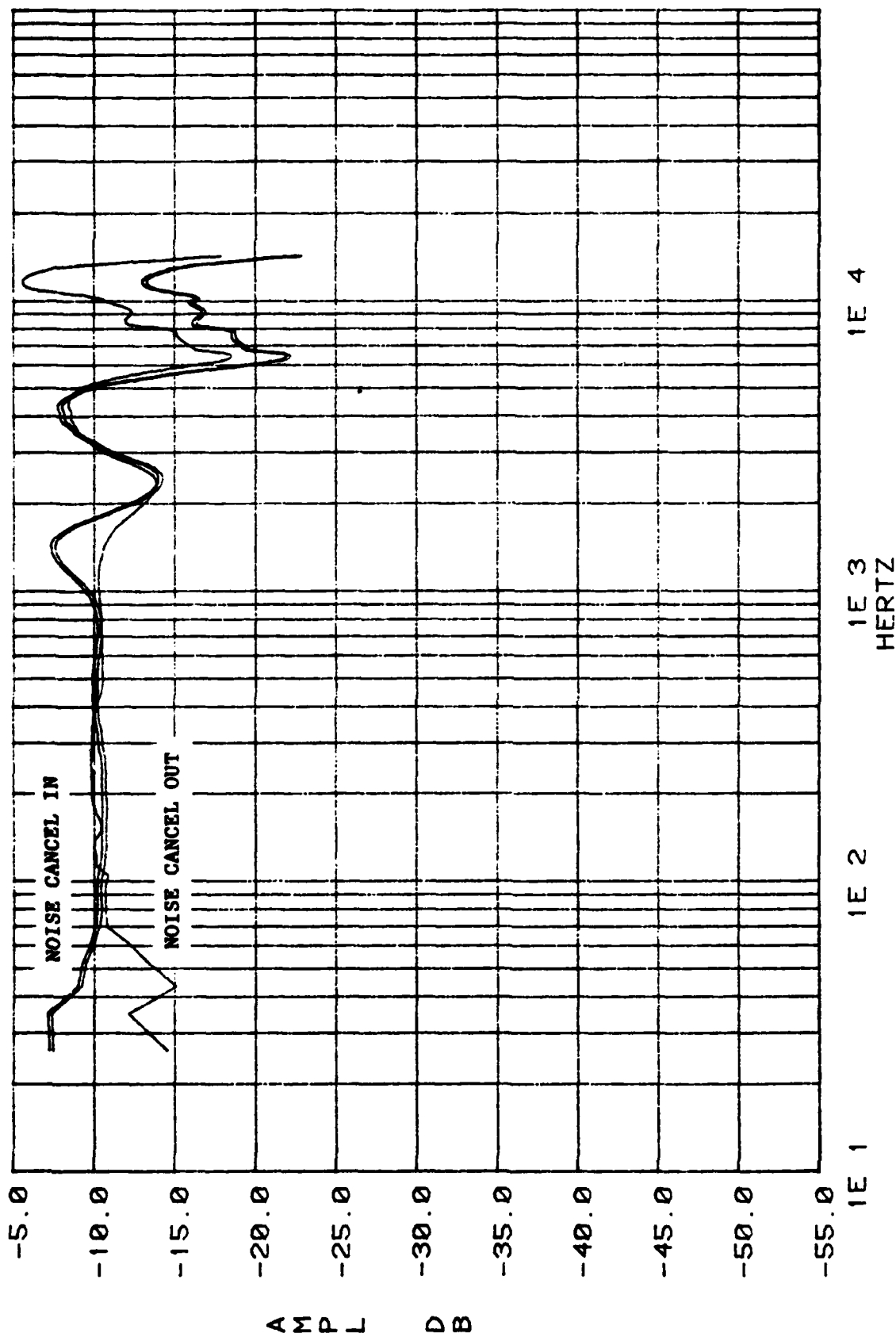


Figure 14. Frequency Response of the 2081-AP System From Communication Input to Earphone Output, Shown With Noise Cancel Switch in Both Positions - Left Channel.

3.0 TEST CONDITIONS

3.1 Source

120 Vac, 60 Hz

3.2 Testing

All electrical and acoustical specifications to be tested after 24 hours continuous operation with pink noise input at an output level of 105 dB SPL.

4.0 ENVIRONMENTAL REQUIREMENTS

4.1 Temperature

Operating: 0° - 50°C (32° - 122°F)

4.2 Humidity

10 - 90 percent

RELATIVE PERFORMANCE

The performance of the BOSE 2081-AF and the standard HGU-26/P earcup enclosure with the H-143/AIC receiver are compared in Figures 16 and 17. The ~~total~~ transmission loss of the 2081-AF system and of the earcup enclosure system is shown as a function of frequency. These measurements were made on a flat plate coupler as described earlier.

Substantial improvements are revealed in the frequency response and transmission loss of the 2081-AF over those of the HGU-26/P earcup enclosure. The effectiveness of feedback in smoothing frequency response can also be seen. The response of the 2081-AF above the loop crossing point is significantly improved over that of the existing driver. The ~~total~~ transmission loss of the 2081-AF also represents an improvement over the HGU-26P earcup with ~~the~~ a minimum attenuation of ~~25/30~~ over 30dB in the region of 60 Hz to 6000 Hz.

DISCUSSION

Behavioral Attenuation Tests

0.1% ANR system
Hearing threshold shift measurement methodology used to describe the performance of ~~the ANR system~~ could yield incorrect results. Active noise reduction differs substantially from passive reduction and special methods may be required to conduct appropriate behavioral attenuation tests. Although physical or objective tests provide useful data, the results do not correlate well with the performance of such devices when worn by humans. Performance measures on human subjects are essential to the determination of ~~their~~ its practical utility.

Oscillation

ANR
In normal use the system should not exhibit any audible audio frequency oscillation. Low frequency oscillations can occur, however, if the earcup is not fit to the head with a proper acoustic seal. This oscillation effect may be eliminated by increasing the force of the earcup against the head or by adjusting the position of the muff on the head ~~to improve the seal~~. High frequency oscillations can also occur when objects are placed inside the driver/microphone cavity. This oscillation will not damage any components and will stop when the objects are removed. This effect can be eliminated during production by placing a protective grill over the driver/microphone cavity. The stability margin of the original design was decreased by the use of the larger sized, high output driver. As noted in the theory section, Appendix II, there is a tradeoff between bandwidth and stability.

Maximum Output

reduction in level
This system is designed to cancel sound ~~fields~~ over a large range of intensities with a ~~limit~~ of about 125 dB(C). This limit neglects the effect of the passive attenuation of the HGU-26/P Helmet which provides very little protection at the low frequencies. The passive attenuation will allow the ANR system to work in ~~such~~ higher sound fields with spectra approximating pink or white noise.

Noise Floor

The level of the electrical noise present in the system is 31 dB(A) and is satisfactory from the standpoint of voice communications.

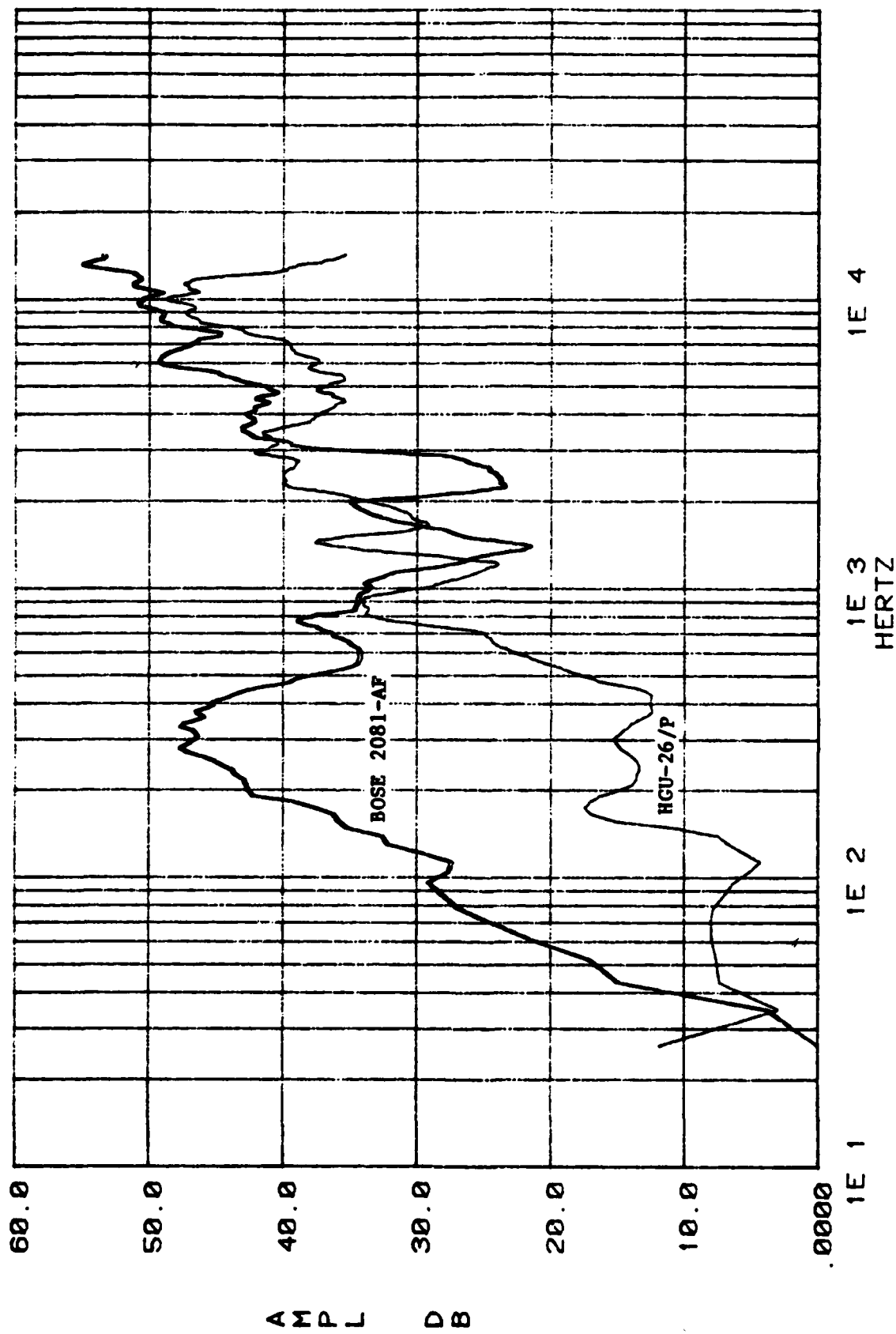


Figure 17. Noise Reduction Comparison of the HGU-26/P Passive Protection System and the BOSE 2081-AF Active Noise Reduction System.

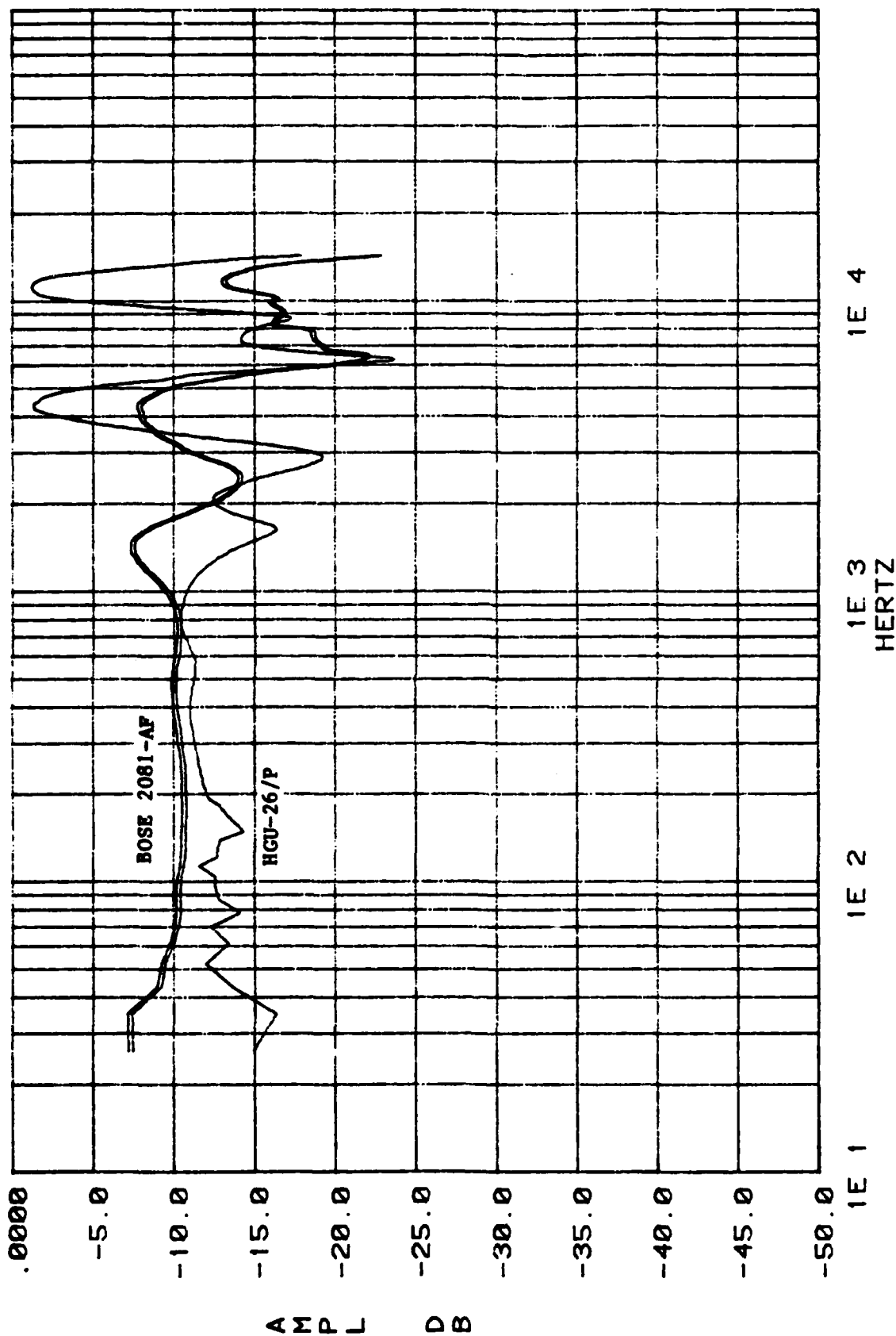


Figure 16. Frequency Response Comparison of the Existing HGU-26/P Passive System and the BOSE 2081-AF Active Noise Reduction System to a Communication Signal.

RECOMMENDATIONS

There are always unanswered questions and topics for further exploration with any research and development. In this program, several areas could be pursued to determine the ultimate suitability of active noise reduction for airborne environments.

The concept of active noise reduction should be adapted to optimize speech intelligibility. This ANR system converted existing technology to form a prototype system to determine its feasibility for Air Force use. It was optimized for improved hearing protection and not for speech intelligibility. Intelligibility improvements can be obtained by reducing noise in the speech band, thus creating a more favorable speech-to-noise ratio. It would be prudent to examine how the ANR system response can be moved up in frequency and if such a move did improve intelligibility.

Field testing of the 2081-AF should be performed to evaluate its performance under realistic conditions. Although considerable attention was given requirements for field conditions during the design of the prototype, prediction of performance in the field is not reliable. Lessons learned from field tests provide a sound basis for designing more advanced models of the system.

Analyses should be performed to define the needs for making the device fieldable in the Air Force. Present military microphones and receivers are not compatible with the ANR system, consequently some development of transducers would be required. The development of the ANR system electronics is not considered a major problem, however to develop the remaining components of the system to be compatible with the Air Force requirements is a significant undertaking.

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APPENDIX I - USER'S GUIDE

This section describes the operation of the 2081-AF prototype. Included is a detailed outline of jacks, connectors, and switch functions and an explanation of a testing procedure. Figure 7 displays front and rear panel layouts. The acoustical package utilized inside the HGU-26/P ear muff is displayed in Figure 4. Figure 18 diagrams the connectors.

Switch Functions

Noise Cancel:

Turns off-and-on noise cancellation feature. When the switch is in the off position, the communication signal, if present, has a frequency response such that it will sound the same as when the switch is in the on position. This switch allows one to experience the effect of noise cancellation alone on a communication signal.

Power:

Connects AC Power to Power Supply.

Connectors:

Headphone:

A keyed circular connector which contains cables going to the headphone drivers and the servo microphones.

Audio Input:

Line level input for speech communication utilizes AF supplied plug for this purpose.

Indicators:

Power:

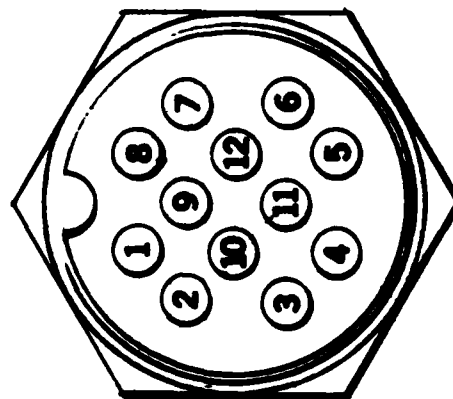
Indicates that power is on and 15V supply is active.

Miscellaneous:

Fuse:

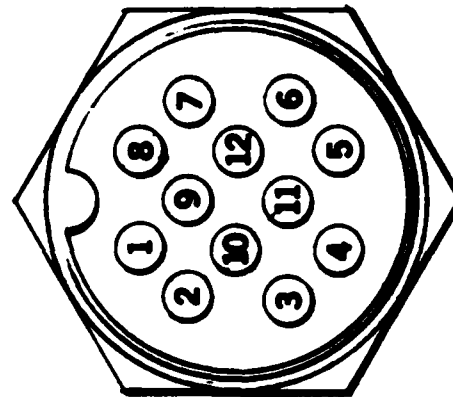
Use 1/4 amp fast blow fuse which is inside the power supply enclosure. Make certain the unit is disconnected before replacing fuse. An Allen wrench is needed to remove the cover.

INTERFACE CABLE CONNECTOR



1. DRIVER SIGNAL, LEFT
2. DRIVER SIGNAL, RIGHT
3. MIC GROUND
4. MIC SIGNAL, RIGHT
5. DRIVER GROUND, RIGHT
6. AIR FORCE MIC -
7. AIR FORCE MIC +
8. NC
9. MIC SIGNAL, LEFT
10. DRIVER SIGNAL, RIGHT
11. MIC BIAS
12. NC

HEADSET CABLE CONNECTOR



1. MIC OUT, LEFT
2. SUMMER INPUT, LEFT
3. MIC OUT, RIGHT
4. NC
5. AUDIO INPUT -
6. AIR FORCE MIC -
7. AIR FORCE MIC +
8. NC
9. MIC BUFFER OUT, LEFT
10. SUMMER INPUT, RIGHT
11. MIC BUFFER OUT, RIGHT
12. AUDIO INPUT +

Figure 18. Cable Connector Diagrams for the Headset Cable (J1) and Interface Cable (J2).

APPENDIX II — THEORY OF DESIGN

The Active Noise Reduction System is a Servo System that is composed of electrical, mechanical, and acoustical elements. A generalized block diagram of a closed loop noise reduction system is shown in Figure 19.

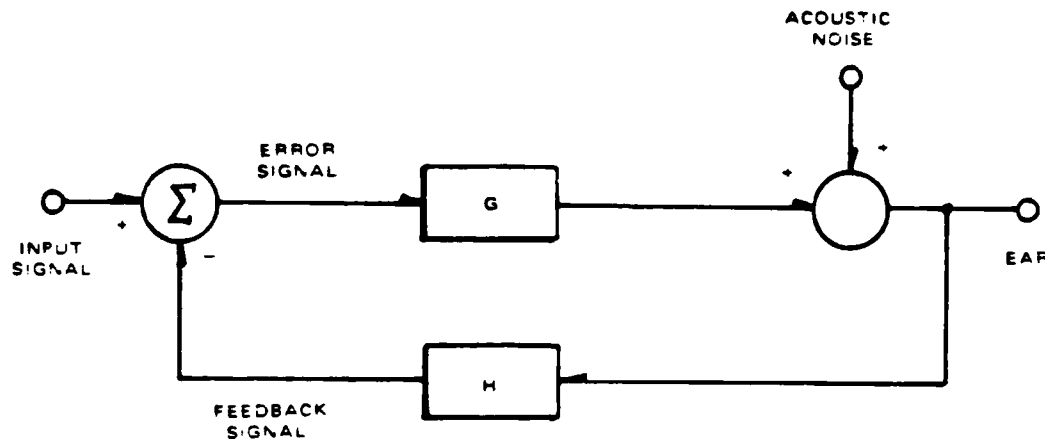


Figure 19. Block Diagram of a Closed Loop Noise Reduction System.

From this block diagram, two transfer functions are derived. One is from reference to output, and the second is from acoustical noise to output. The reference is the input to the system and typically would be connected to a speech communication signal. Both of these will be derived for the closed loop configuration and the open loop configuration. Neglecting the noise for the moment, it can be seen that the block diagram represents a standard servo system with the transfer function:

$$(1) \quad \frac{\text{Output}}{\text{Reference}} = \frac{G}{1 + GH} \quad (\text{closed loop})$$

and if the feedback path is broken:

$$(2) \quad \frac{\text{Output}}{\text{Reference}} = G \quad (\text{open loop})$$

To derive the gain from noise input to output, the block diagram can be redrawn as shown in Figure 20.

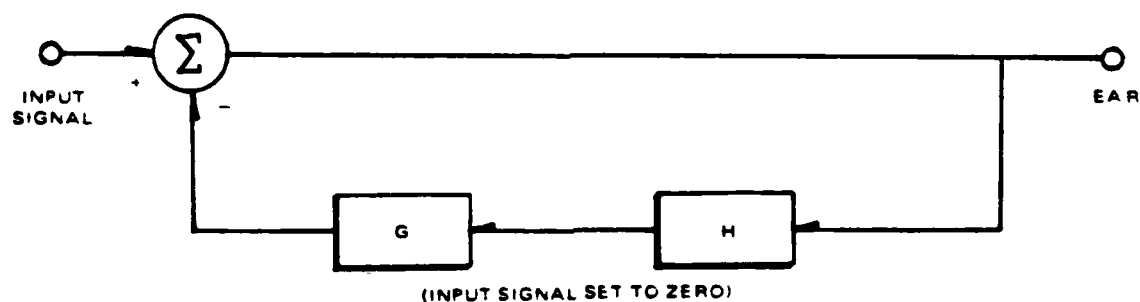


Figure 20. Block Diagram of a Closed Loop Noise Reduction System Treating Noise as the Input.

The ratio of output to noise input has a similar form as the ratio of output to reference. By noticing that the forward gain is unity, and the feedback is now GH , the transfer function is:

$$(3) \quad \frac{\text{Output}}{\text{Noise}} = \frac{1}{1 + GH} \quad (\text{closed loop})$$

If the feedback path is broken, the following results:

$$(4) \quad \frac{\text{Output}}{\text{Noise}} = 1 \quad (\text{open loop})$$

By taking the ratio, the amount of noise reduction can be derived:

$$(5) \quad \frac{\text{Output Noise}}{\text{Output Noise}} \quad \frac{\text{Closed Loop}}{\text{Open Loop}} = \frac{\text{Output Closed Loop}}{\text{Output Open Loop}} = \frac{1}{1 + GH}$$

Thus, it can be seen that the noise reduction of this system is $1 + GH$, or for high loop gains, equal to the open loop gain. Equation (1) becomes with unity gain feedback ($H=1$) and high gain:

$$(6) \quad \frac{\text{Output}}{\text{Reference}} = \frac{G}{1 + GH} \approx \frac{G}{1 + G} \approx 1$$

Equation says that for high gain and unity gain feedback, which are both typical for the active noise reduction system, the frequency response will be flat from input to output. This means that the feedback system will compensate for response irregularities in the driver/ear cup transfer function. This is discussed further in the "Electroacoustic Performance and Engineering Specifications" section.

The theory of operation of the prototype can be described by referring to Figure 21.

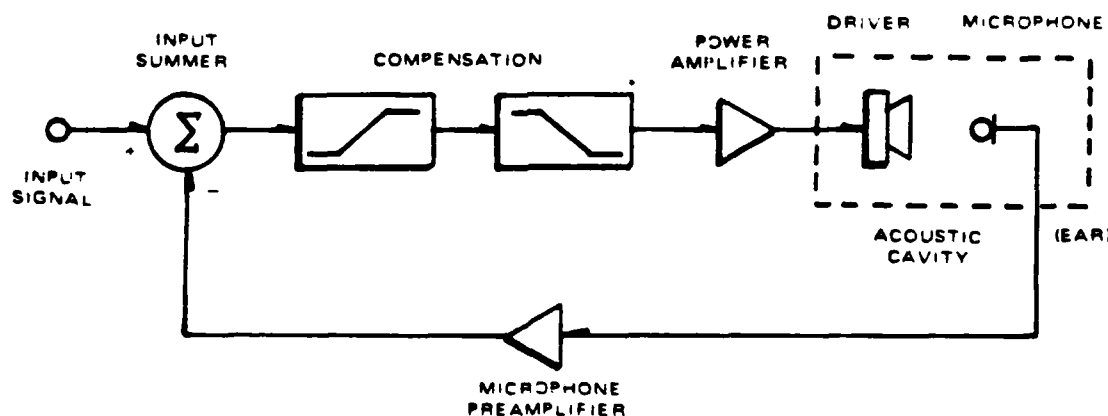


Figure 21. Block Diagram of a BOSE 2081-AF Active Noise Reduction System.

RECEIVERS

When the ear senses the same pressure as the microphone, then the signal at the ear is reduced by $1 + GH$ when the system is activated. Since this is a linear system, the components of operation are additive. Therefore, active noise reduction will occur even while there is an input (or reference signal). Furthermore, since passive attenuation operates to reduce the pressure at the ear, the effects of passive and active transmission loss can be added. Thus, active attenuation can be used to compliment passive attenuation to provide high overall attenuation at low frequencies.

There are certain other considerations which impact performance because this is a feedback system. Probably the most important is stability of the feedback loop. By marginal design, it is possible to create an instability which will create oscillation. This will occur when the gain is 1 and there is 180° of phase shift in the loop. If the phase margin is increased, the loop will not oscillate, but it is possible to have peaking of the response.

This peaking has two side effects; first, it causes noise enhancement because the magnitude of the noise reduction function $1 + GH$ is now less than 1. Second, it causes the closed loop response to have a peak in the frequency response which may impair speech quality. There is a tradeoff in loop bandwidth and stability. Since there is a time delay in the system (from the driver to the microphone) the loop bandwidth cannot be extended indefinitely. As the bandwidth is extended the phase, due to the time delay, is increased. Since the phase affects stability, the time delay imposes a fundamental limitation on system performance.

The prototype supplied suffers to some extent from oscillation because it was desired to both meet the original noise cancellation specifications and utilize a larger driver with higher output capability. In order to reduce the possibility of oscillation, the diameter of the ~~drive~~ ^{driver} can be reduced to minimize time delay. Alternately, the gain of the system can be reduced.

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